So you Think You Have A Geothermal Resource!! –Now What?

Presentation for

Geothermal Investor's Forum

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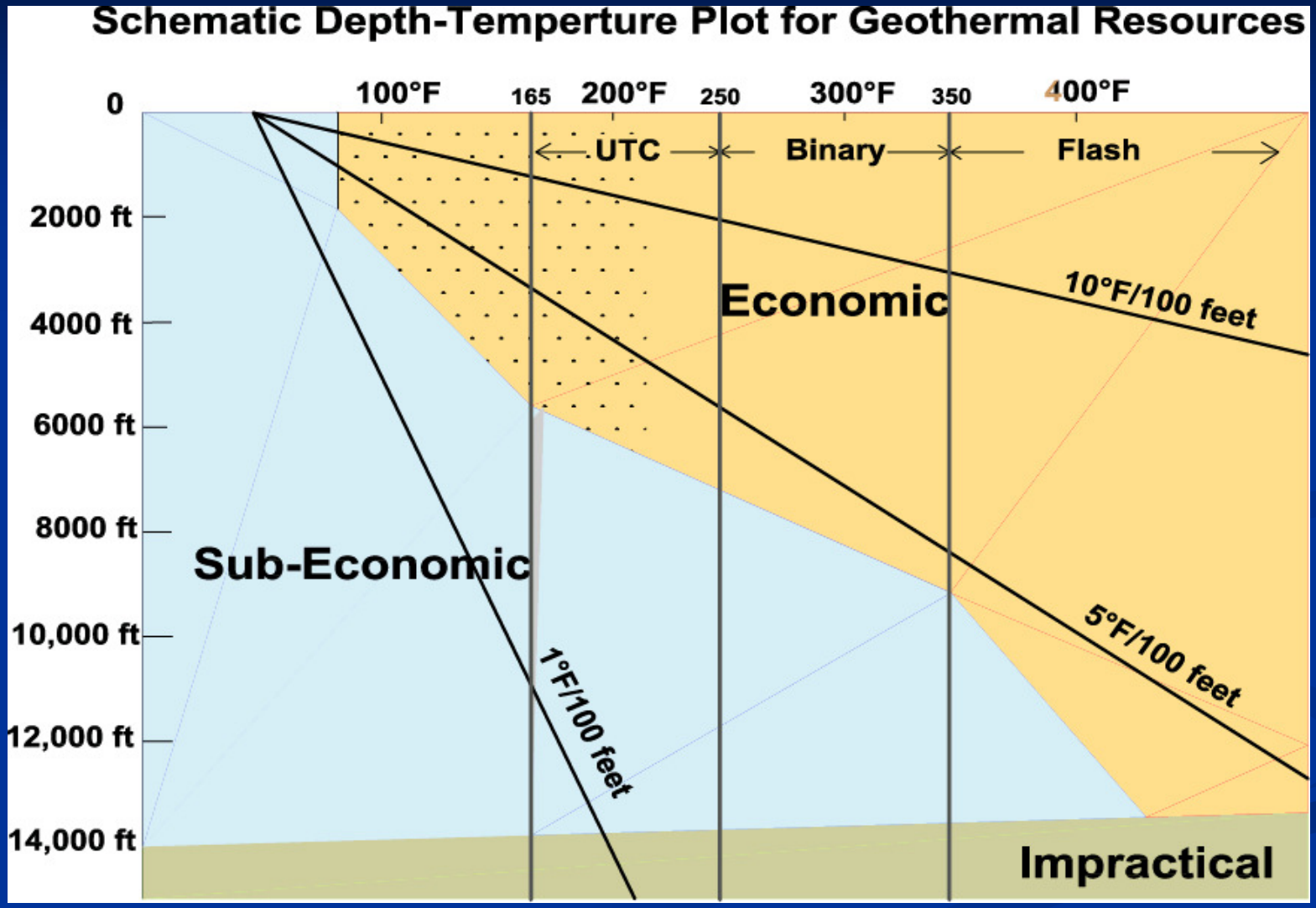
Geothermal Systems Characteristics

- A heat source (magmatic or non-magmatic)
- Convective upflow
- Recharge by meteoric waters
- Deep mixing with meteoric waters and/or condensate
- Outflow of the deep fluids to the surface or other hydraulic base level

Almost all geothermal systems require the presence of fractures to allow movement of fluids from depth into the shallow surface


Schematic Depth-Temperture Plot for Geothermal Resources
0
2000 ft
4000 ft
6000 ft
8000 ft
10,000 ft
12,000 ft
14,000 ft
100°F
165
200°F
250
300°F
350
400°F
UTC
Binary
Flash
Economic
Sub-Economic
Impractical
10°F/100 feet
5°F/100 feet
1°F/100 feet

Resource Settings

Type A - Magma-heated, dry steam resources (The Geysers)

Type B - Andesitic volcanic resources (Philippines, Indonesia, Central & South America)

Type C - Caldera resources (Medicine Lake, Valles Caldera, Los Humeros, Yellowstone)

Type D - Sedimentary–hosted, volcanic-related resources (Imperial Valley)

Type E - Extensional tectonic, fault-controlled resources (Great Basin)

Type F - Oceanic-ridge, basaltic resources (Hawaii, Iceland, Azores)

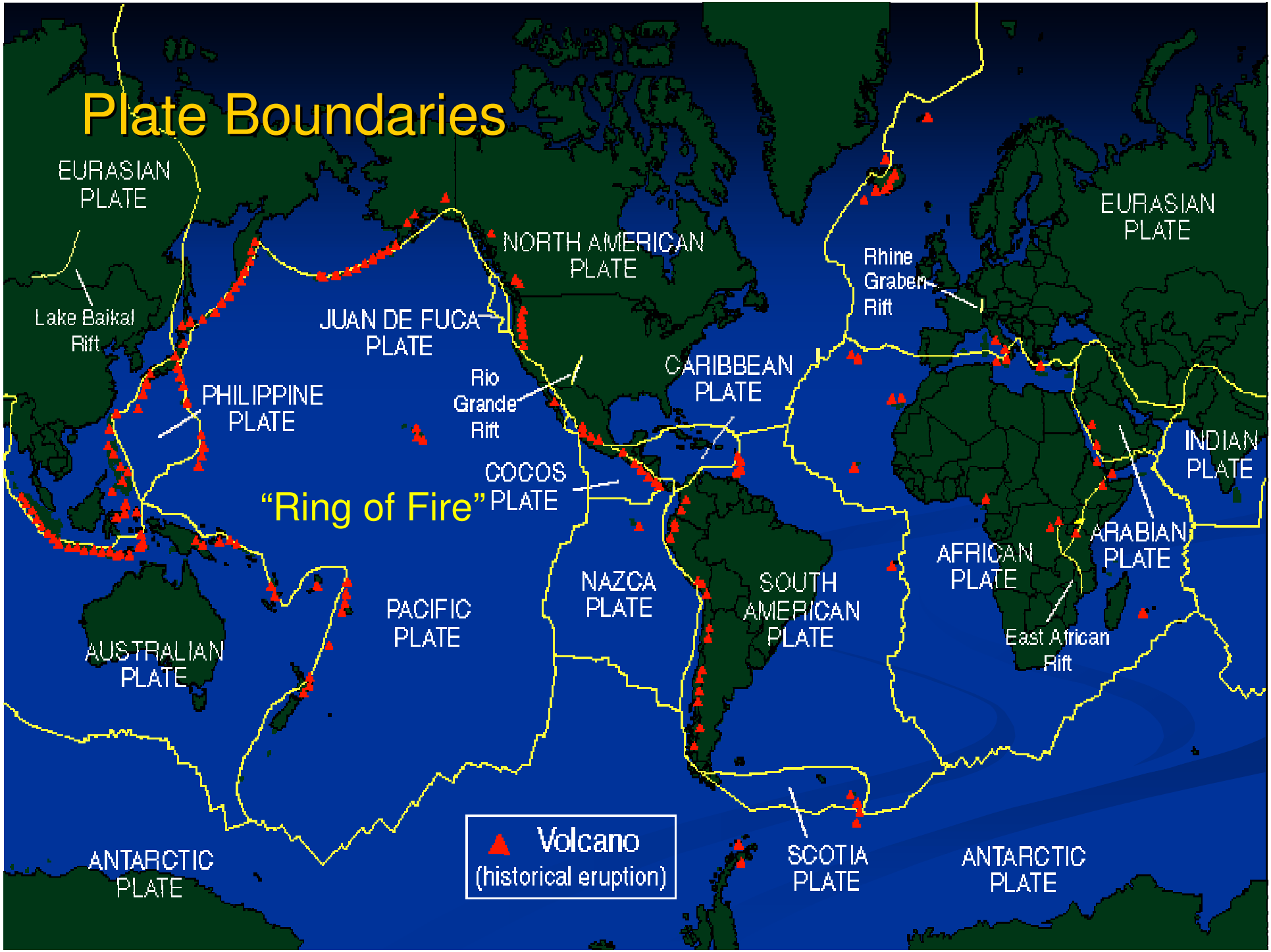
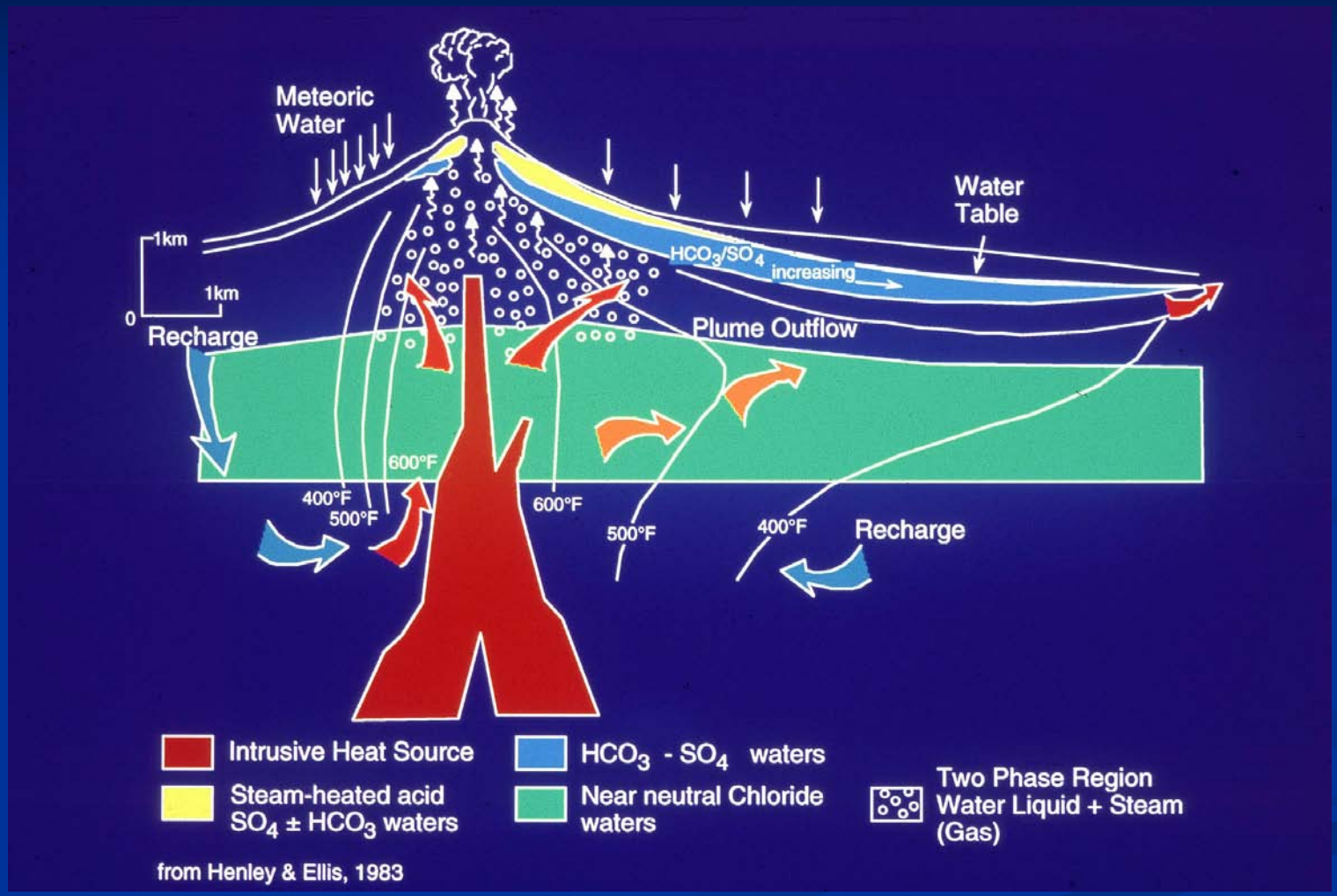


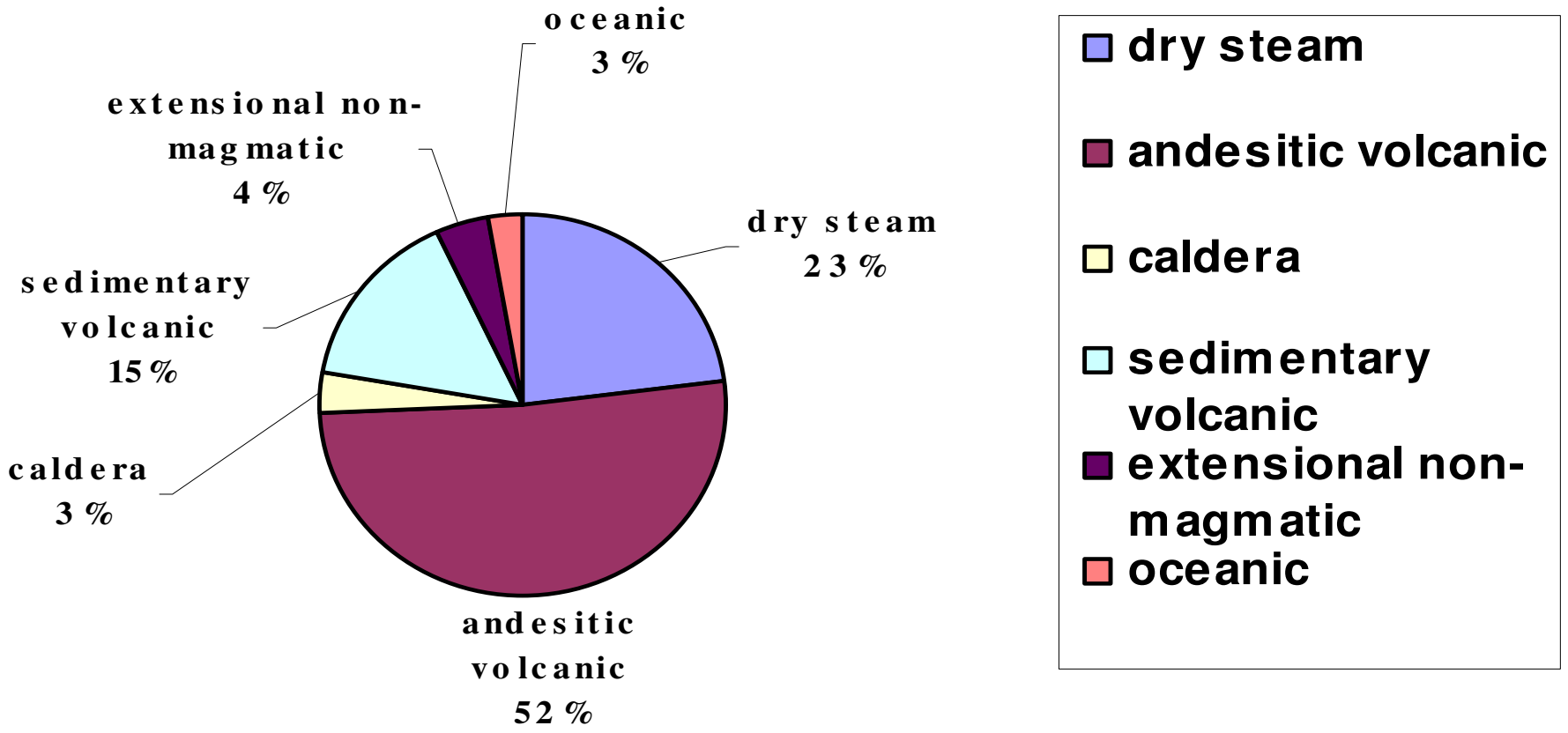
Plate Boundaries
EURASIAN PLATE
Lake Baikal Rift
NORTH AMERICAN PLATE
JUAN DE FUCA PLATE
PHILIPPINE PLATE
Rio Grande Rift
CARIBBEAN PLATE
Rhine Graben Rift
EURASIAN PLATE
INDIAN PLATE
COCOS PLATE
"Ring of Fire"
ARABIAN PLATE
AFRICAN PLATE
NAZCA PLATE
SOUTH AMERICAN PLATE
PACIFIC PLATE
East African Rift
AUSTRALIAN PLATE
Volcano
(historical eruption)
SCOTIA PLATE
ANTARCTIC PLATE
ANTARCTIC PLATE

Conceptual Model of an Andesitic Volcano

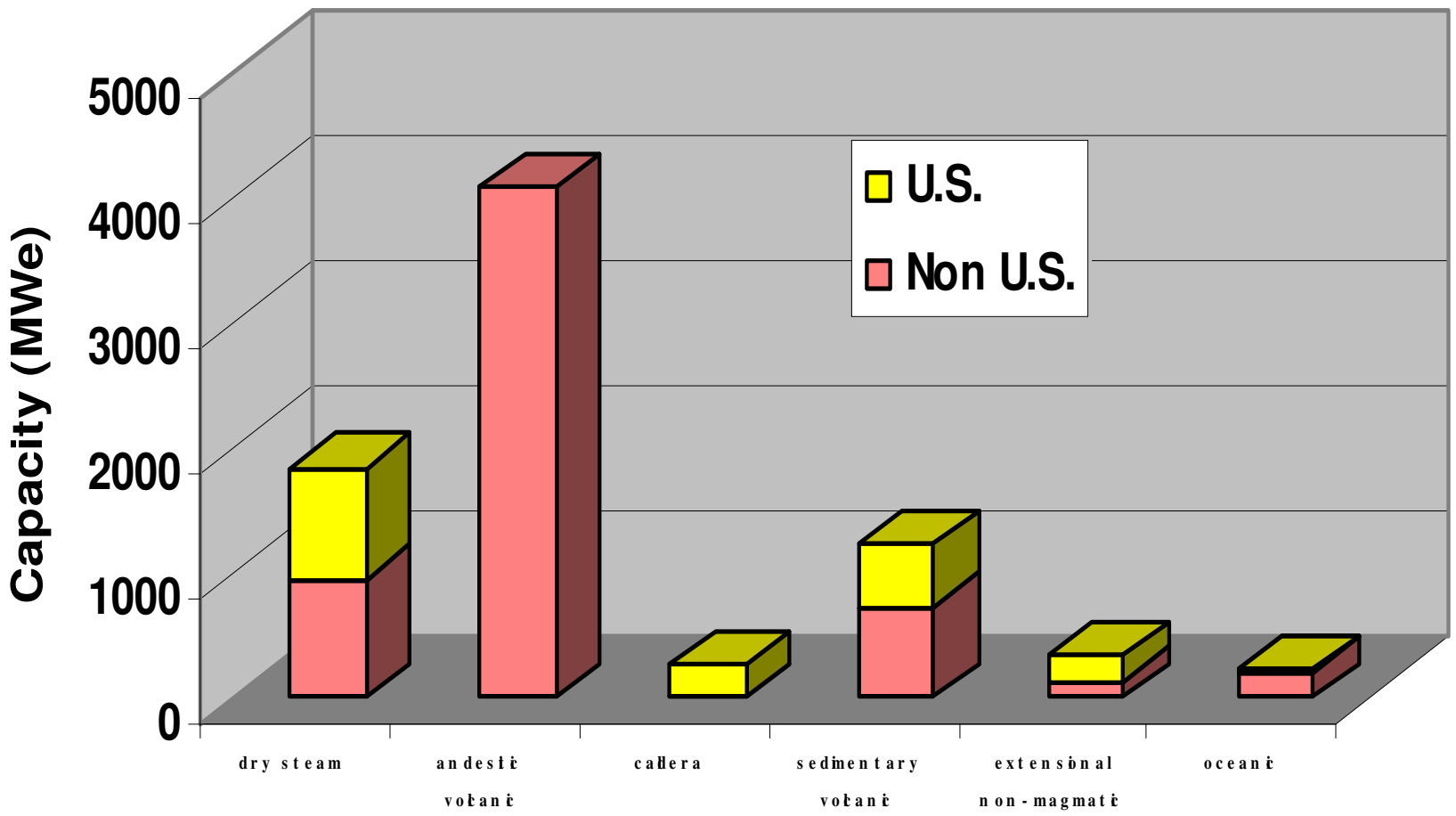


(Henley and Ellis, 1985)

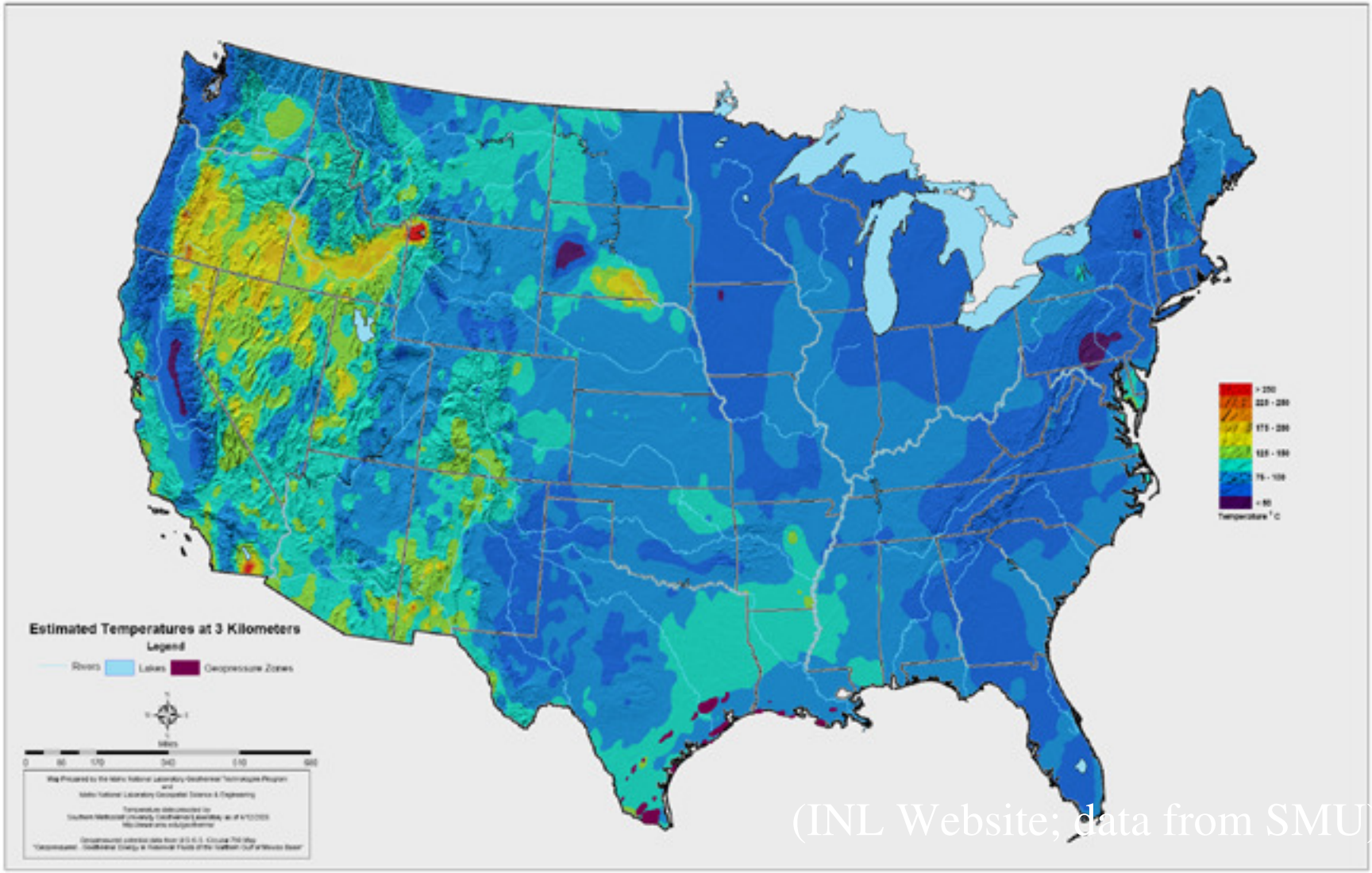
Worldwide Geothermal Resource Types



U.S. Proportion of World Geothermal Reources



Temperatures at 3 km Depth



EXPLORATION APPROACH

- Remote Sensing Data (REGIONAL)
- Geologic/Structural and Surface Manifestations Mapping (REGIONAL/EXTENDED PROJECT AREA)
- Geochemical Sampling and Analysis (EXTENDED PROJECT AREA/PROJECT)
- Geophysical Surveys (PROJECT)
- Exploration Drilling (PROJECT)

    Temperature Gradient/Heat Flow

    Exploration (Core) Wells

6. Production Well Drilling (PROJECT)

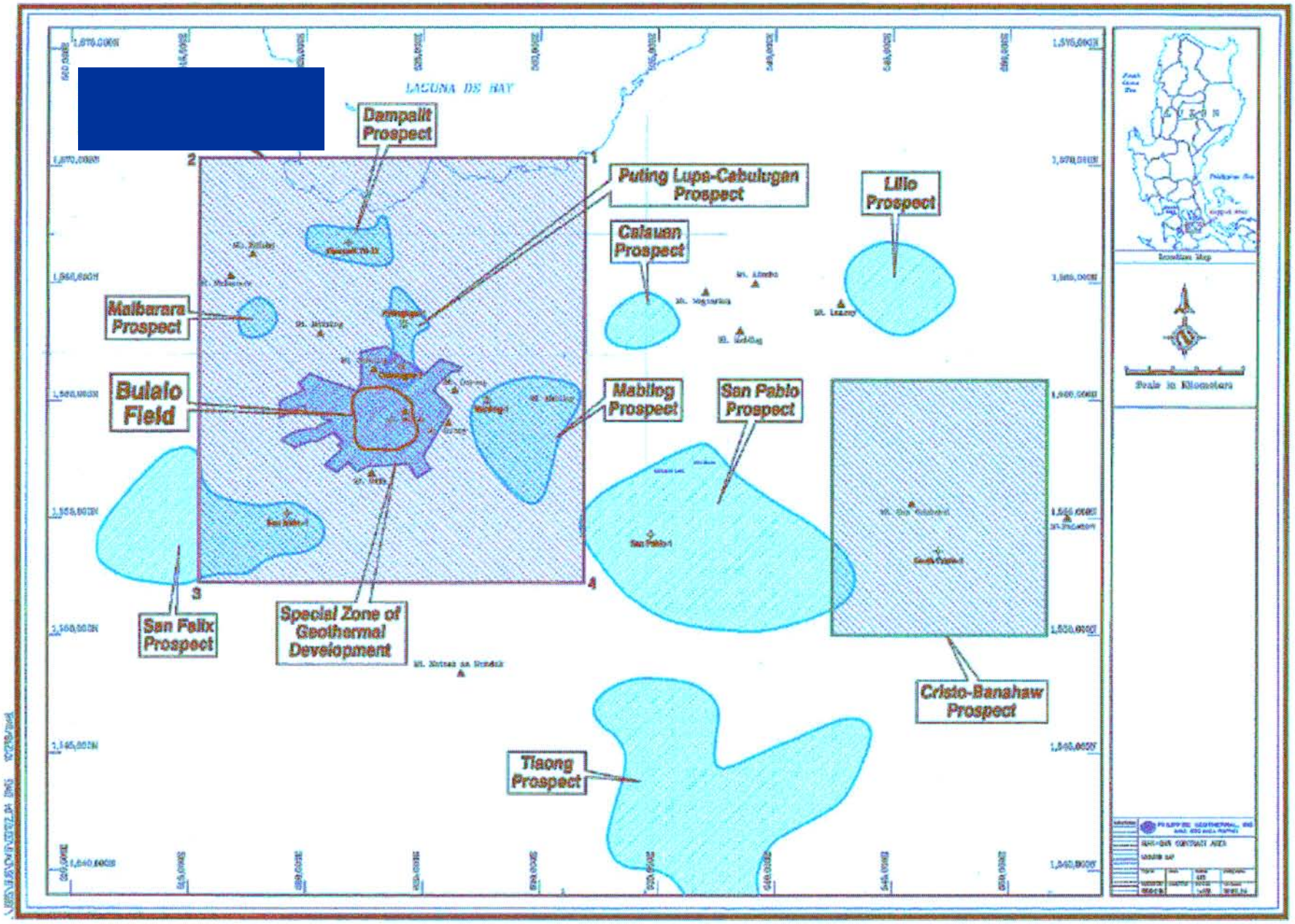

LAGUNA DE BAY
Dampalit Prospect
Puting Lupa-Cabulugan Prospect
Lilio Prospect
Calauan Prospect
Malbarara Prospect
Bulalo Field
Mabilog Prospect
San Pablo Prospect
San Felix Prospect
Special Zone of Geothermal Development
Cristo-Banahaw Prospect
Tiaong Prospect
1
2
3
4
Scale in Kilometers

Figure 1

Remote Sensing Data Types

- Multispectral (several relatively broad bands)
- Hyperspectral (many narrow bands)
- Thermal Infrared (TIR – can be multispectral)
- Panchromatic (gray scale – single very broad band)
- Radar (microwave)
- LIDAR (LIght Detection and Ranging - laser)
- High/Low Altitude Photography

Geology /Structural Techniques

- Regional Structural Analysis
  - Regional Seismicity, Stress Field
  - Geometry of Fracture systems
- Regional Geologic Mapping
  - Rock Lithologies
  - Mapped Faults
- Rock Alteration
  - Alteration mineralogy
  - Alteration Assemblages
  - Duration of Geothermal Systems

Geochemistry

Chemical characteristics of:

- waters, gases, rocks, and soils

Geothermometers

- silica geothermometers
- Na-K-Mg-Ca geothermometers
- sulphate oxygen isotope

Tracers

Isotopes

STABLE ISOTOPES OF WATER

Isotope	Ratio (R)	% Natural abundance	Reference Standard	Common Precision of H_2O Analysis
^{2}H Deuterium	$^{2}H/^{1}H$	0.015	VSMOW	$\delta D \pm 1.0$ o/oo
^{18}O	$^{18}O/^{16}O$	0.204	VSMOW	$\delta^{18}O \pm 0.1$ o/oo

δD or $\delta^{18}O$ = 1000 * (Rsample – Rstd)/Rstd (permil or o/oo)

So:

Seawater δD = 0 o/oo and $\delta 18O$ = 0 o/oo

δD or $\delta 18O < 0$ = “lighter”

δD or $\delta 18O < 0$ = “heavier”

$H_2{}^{16}O$ is about 10% lighter than $H_2{}^{18}O$, and chemically more reactive

Solutes: Major Anions

Chloride

~50 to ~20,000 mg/kg

(to ~200,000 mg/kg in hypersaline brines)

Sources: traces of Na-K-Cl in volcanic rocks (seawater origins), connate seawater in sedimentary rocks, halite deposits

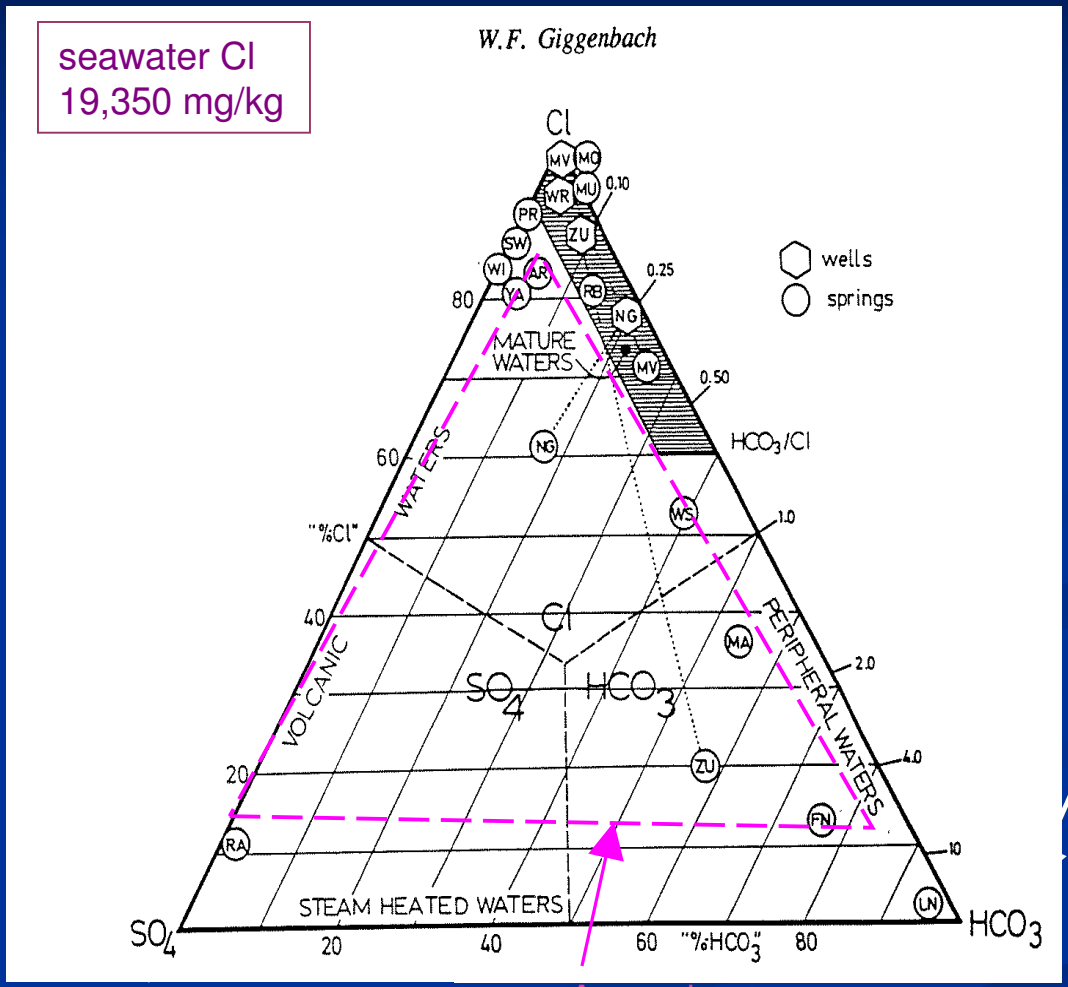
Sulfate

~10 to ~1500 mg/kg

(to ~100,000 mg/kg in acid volcanic steam condensates

Sources: oxidized sulfide minerals and H_2S, sulfate mineral deposits (gypsum, anhydrite)

seawater Cl 19,350 mg/kg



Extremes of volcanic and steam heated are acidic (no HCO3)

Approximate range among non-volcanic geothermal systems (higher SO_4 exist)

Bicarbonate

<1 to several 1000 mg/kg

(for most purposes, effectively the same as "alkalinity")

Sources: reactions of dissolved CO_2 from atmosphere and/or in geothermal/volcanic steam, with silicate minerals in rocks, with carbonate minerals (limestone)

Geophysical Techniques

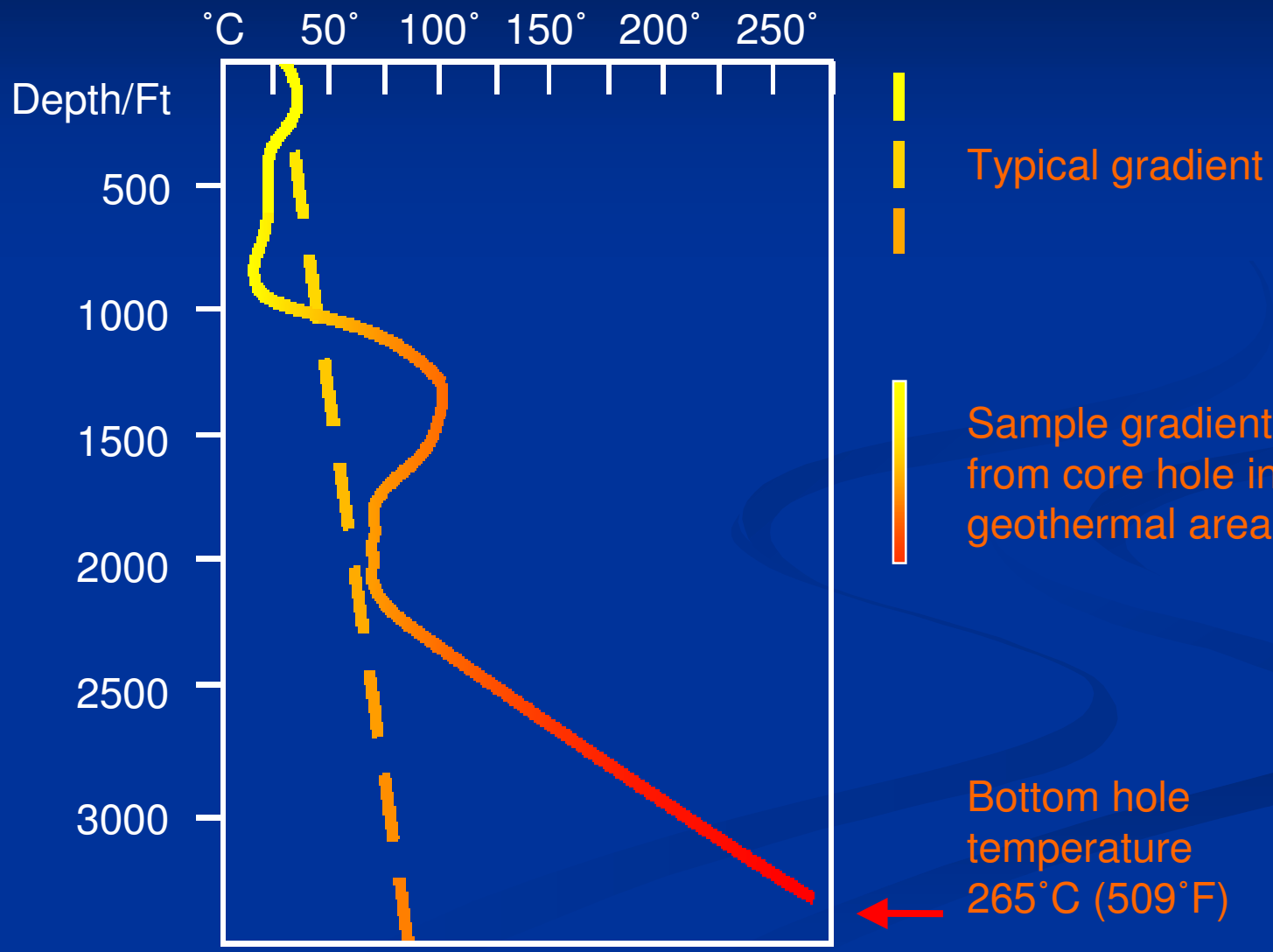
Standard: MT, T-MT, TDEM, Gravity

Legacy: Dipole-Dipole, tensor Dipole-Bipole

Special: VES, AMT, CSAMT, SP, HEM, Aeromagnetics, Precision Ground magnetics, Reflection/Refraction Seismics

Development: Microgravity, Micro-earthquakes, Subsidence

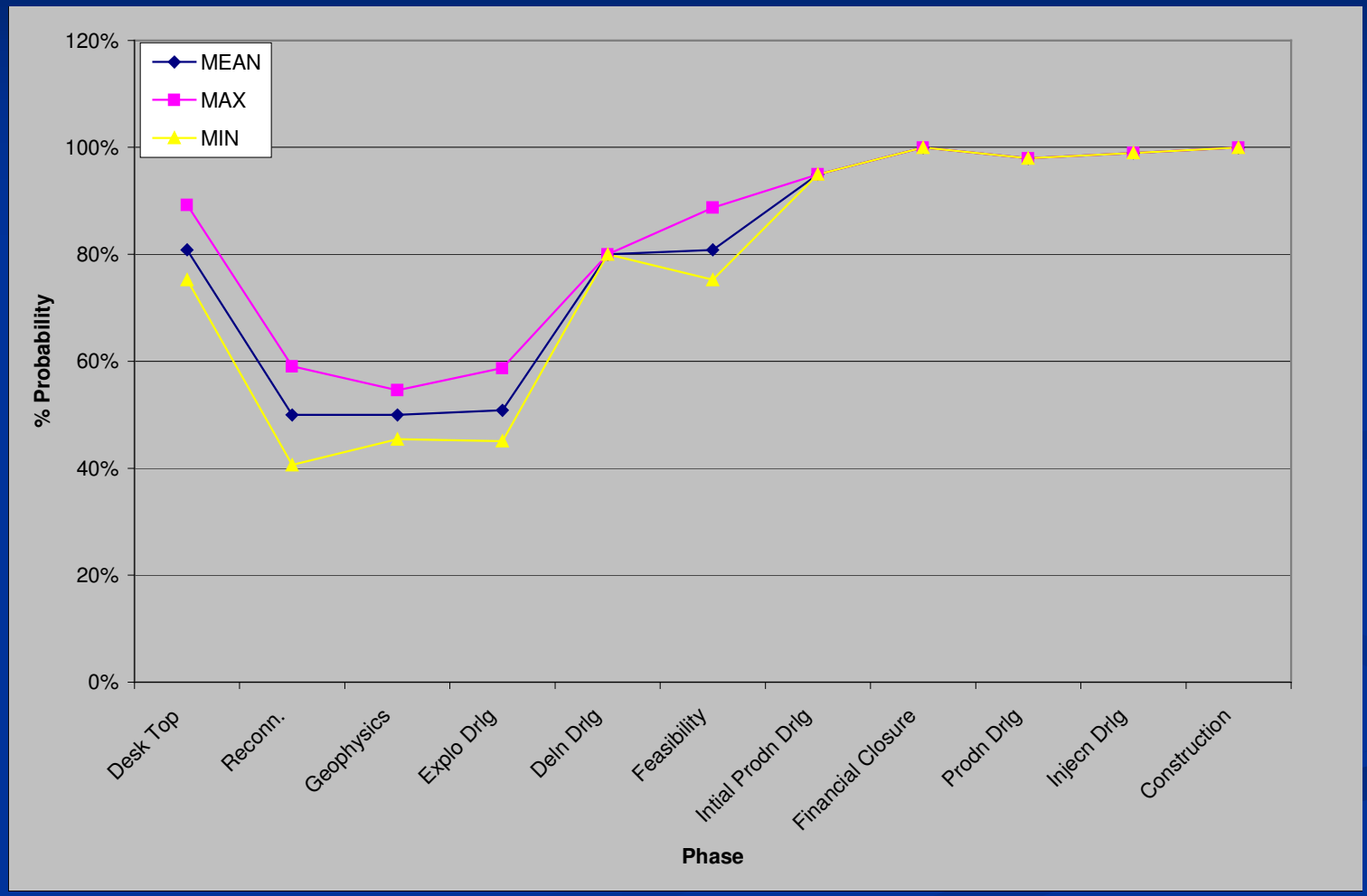
Sample Temperature Gradient Data



Discovery to Developed…

Shooting fish in a barrel?

Probability of Success for any Stage



Probability of Proving a Viable Project